Solar Thermophotovoltaic Power Generation System Using Spectrally Controlled Monolithic Absorber/Emitter

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論 文 内 容 要 旨

Energy security has been increasingly important issues around the world. Especially, Japan shows low energy security level comparing to the other countries. This is based on low self-sufficiency ratio in the primary energy supply, the import dependence of oil, and so on. Indeed, according to the Great Japan Earthquake 2011, the energy security level of Japan has got more serious after Fukushima Daiichi Nuclear Power Station Accident. In order to improve energy security level in Japan, it is crucial to increasing the self-sufficiency ratio in the primary energy supply, and maintaining stable energy supply. Renewable energy resources can realize to constantly replenish and will never run out. It is also a great advantage that the both the emission of greenhouse gases such as carbon dioxide (CO_2) and the small impact on the environment are small. Reducing the energy import rate by using renewable energy is beneficial from the viewpoint of energy security.

Solar energy, which is one of the typical renewable energy, provides consistent and sustainable energy source. Photovoltaic cells are known well as a method for generating electric power converted from the solar energy. Si single-junction cells have achieved efficiencies around 25%, on the other hand, single-junction PV cells cannot overcome Shockley Queisser limit. Multi-junction cells can overcome the efficiency limit, by multiple p–n junctions consisted of different semiconductor materials. The efficiency of multi-junction cells has been established around 46%, higher efficiency than that of single-junction cells. However, the costs of the multi-junction cells are high compared to that of the single-junction cells because of difficult fabrication. In addition, solar energy can be used as heat source, which enables to realize solar thermal storage. Therefore, solar energy has a potential as energy resource to provide various energy utilization.

A Solar-thermophotovoltaic (TPV) system operates using concentrated solar energy and is mainly composed of an absorber, an emitter, and TPV cells. The absorber, heated by the concentrated solar energy, increases the emitter temperature and the TPV cell generates electricity using the received thermal radiation from the emitter. The full spectrum of solar energy can be used in Solar-TPV systems by controlling emitter spectra. High conversion efficiency can be realized even with single-junction cells by matching the thermal radiation from the emitter with the spectral response of a TPV cell. Solar-TPV systems have potentially high efficiency; however, the obtained experimental efficiency is still much lower than the theoretically predicted efficiency.

The motivation and objective of this dissertation is to establish the design guideline and fundamental technology for obtaining high-efficiency Solar-TPV systems. The power generation tests of Solar-TPV systems were demonstrated for proof of concept. The structure of this dissertation is as follows:

Chapter 1: General introduction and background

Chapter 2: Design of Solar-Thermophotovoltaic systems

Chapter 3: Narrowband thermal radiation from closed-end microcavities

Chapter 4: Spectrally controlled absorber/emitter based on coherent perfect absorption

Chapter 5: Power generation tests of Solar-TPV systems

Chapter 6: Conclusions

Chapter 1: Introduction

The background of this thesis is presented. A historical development of TPV systems, mainly the components technology of selective absorber and emitter, and photovoltaic cells are denoted. The state-of-the-art Solar-TPV systems are mentioned. The motivation and objective of this study are described.

Chapter 2: Design of Solar-Thermophotovoltaic systems

The contribution of spectral and geometric design of absorber/emitter is evaluated to design high-efficiency Solar-TPV systems based on the both photovoltaic conversion efficiency (η_{PV}) and unidirectional radiative heat extraction efficiency ($\eta_{extraction}$). High η_{PV} can be achieved by narrowband emission with high Q factor from the emitter because heat and transmittance losses are suppressed in TPV cells. It is also important to suppress the emissive power from the emitter in the long wavelength ranges to decrease the losses corresponding to the emission below Eg. In order to design spectral property of the emitter, it is necessary to consider Q factor, emissivity peak of the emitter, temperatures and emissivity value in the long wavelength ranges. With the emissivity value 0 in the long wavelength ranges, the η_{PV} increases with high Q factor. With the emissivity value 0.15 in the long wavelength ranges, the maximum η_{PV} = 24% is achieved with Q factor = 5. The radiative heat transfer efficiency $\eta_{extraction}$ was defined and investigated, which is defined as the ratio of the emissive power from the emitter to the total input power; the latter can be calculated from the reflection and emission from the absorber, and the emission from the emitter. It is crucial to control all the power factors from the absorber/emitter, such as the reflection and emission from the absorber, and the emission from the emitter to obtain a high $\eta_{extraction}$. The spectral control of absorber and increasing area ratio of emitter-to-absorber contributes to the increasing $\eta_{extraction}$. The trade-off between two efficiencies of η_{PV} and $\eta_{extraction}$ exists, then, $\eta_{extraction}$ decreases with increasing Q factor, resulting in low system efficiency (η_{system}). High η_{system} with increasing high area ratio is expected by geometric control as well as spectral control of absorber and emitter. Therefore, the guideline for obtaining high-efficiency Solar-TPV systems has been obtained.

From this study, we established the design guideline for obtaining high-efficiency Solar-TPV systems. This consideration will contribute to design overall Solar-TPV systems and improve the efficiencies.

Chapter 3: Narrowband thermal radiation from closed-end microcavities

Narrowband thermal radiation for high-efficiency Solar-TPV systems is designed and observed based on a closed-end microcavity, which is a conventional open-end microcavity covered by a semi-transparent thin metal film. Narrowband emission with high Q factor from the emitter can contribute high η_{PV} because heat and transmittance losses are suppressed in TPV cells. A closed-end microcavity in which a semi-transparent metal film was formed atop the open-end microcavity was designed to achieve narrowband and low angular dependency absorption/radiation spectrum for high-efficiency Solar-TPV systems. The Q factor of the optical emission band strongly depended on the electrical conductivity of the metal thin films. An asymmetric and narrow emission band with the Q factor of 25 at 1.28 µm was obtained by the closed-end microcavity. The numerical simulations suggest that the formation of a fixed-end mode at the cavity aperture contributes to the narrowband optical absorption. According to the numerical simulation, the closed-end microcavity filled with SiO_2 exhibits intense and isotropic thermal radiation over a wide solid angle. The narrow and asymmetric absorption spectrum was experimentally confirmed in the model of closed-end microcavity. The design of closed-end microcavity emitter is achieved in which Q factor can be controlled by choosing materials and film thickness formed at microcavity top of a closed-end microcavity.

High Q factor narrowband thermal radiation has been designed and observed based on closed-end microcavity structures in this chapter. This technology will be contributed to improve η_{PV}, resulting in high-efficiency Solar-TPV systems.

Chapter 4: Spectrally controlled absorber/emitter based on coherent perfect absorption

The spectrally selective absorber/emitter based on coherent perfect absorption phenomenon (CPA) is proposed. The absorber/emitter is expected to obtain high thermal stability by means of refractory materials and also easy fabricated. The spectrally selective absorber/emitter based on CPA composed of a thin Mo layer sandwiched between HfO_2 layers was investigated to employ Solar-TPV systems. The absorptance cutoff and absorption intensity at short wavelengths are strongly related to the thicknesses of the Mo and HfO_2 layers. The optimized emitter provides η_{PV} of 28% at 1500K, which exceeds Shockley Queisser limit of 19.6%. The optimized absorber provides the extraction efficiency for absorber: $\eta_{extraction}$ of 51% at 1500K. These results suggested that the selective absorber/emitter employing CPA phenomenon can achieve low absorptance value in the long wavelength ranges by its substrate polished by small slurry-particle in mechanical chemical polishing process. These results will contribute to suppress emission losses from absorber and emitter, resulting in high $\eta_{extraction}$, η_{PV} and η_{system}.

The selective absorber/emitter based on CPA with high $\eta_{extraction}$ and η_{PV} was designed. The high thermal stability can be expected for Solar-TPV systems, and easy-fabrication. The selective absorber and emitter can be expected to obtain high $\eta_{extraction}$ and η_{PV}, resulting in high-efficiency Solar-TPV systems.

Chapter 5: Power generation tests of Solar-TPV systems

The demonstrations of Solar-TPV systems are implemented using the planar monolithic absorber/emitter systems with area ratio of emitter-to-absorber considering the efficiency of unidirectional radiative heat transfer efficiency. The planar absorber/emitter is designed based on unidirectional radiative heat transfer efficiency as discussed in Chapter 2. The absorber/emitter is consisted of Mo and HfO_2 layer structures based on the CPA concept as presented in Chapter 4. The $\eta_{extraction}$ was investigated with respect to the area ratio of emitter-to-absorber considering the configuration implemented in this thesis. It is crucial to control all the power factors from the absorber/emitter, such as the reflection and emission from the absorber, and the emission from the emitter and the Mo area on the absorber side, to obtain high $\eta_{extraction}$. It was learned and demonstrated that high

$\eta_{extraction}$ contributes high-efficiency Solar-TPV systems. The fabricated absorber/emitter achieved a system efficiency of 5.1% at maximum when the absorber/emitter area ratio was 2.3 with a GaSb TPV cell, which is cost-effective and wider bandgap compared to InGaAsSb cells. The cube-type absorber/emitter system is also proposed to further improve $\eta_{extraction}$. The higher $\eta_{extraction}$ = 62% is observed at 1275 K by cube-type absorber/emitter systems. From this results, the η_{system} = 7.8% is expected from this cube-type absorber/emitter systems, which is based on further improving of $\eta_{extraction}$ = 67% compared to $\eta_{extraction}$ = 44% for planar absorber/emitter systems.

The power generation tests of Solar-TPV systems based on high $\eta_{extraction}$, has been established and demonstrated for proof of concept. These results will be expected to be a breakthrough to establish high-efficiency Solar-TPV systems.

Chapter6: Conclusions

The results obtained in this dissertation are summarized to conclude this dissertation.

論文審査結果の要旨

エネルギーを安定的かつ適切に供給することは世界各国共通の課題である。再生可能エネルギーはエネルギー源の多様化や地球温暖化対策に資することができ，再生可能エネルギー利用の技術開発をより積極的に推進していくことは重要である。再生可能エネルギーの中でも，太陽エネルギーは地域を限定せずに利用可能であり，また，様々な形態による利用開発が求められている。全固体型の高効率な太陽熱利用発電として期待される太陽熱光起電力発電（Solar-thermophotovoltaic: Solar-TPV）システムは，集光太陽光，太陽光選択吸収材料，波長選択エミッタ，光電変換セルから構成される。Solar-TPV システムでは，集光太陽光により太陽光選択材料・波長選択エミッタが加熱された後，波長選択エミッタからの感度波長域に合わせた熱ふく射により光電変換セルが発電を行う。太陽光をいったん熱に変換することにより，太陽光のもつ光子エネルギーを保存したまま，光電変換セルの感度波長域に合わせた熱ふく射へ変換することが可能になるため，安価な単接合太陽電池を用いても高効率な発電が可能となる。Solar-TPV システムは潜在的に 40%以上の発電効率が期待できる一方で，実験的に達成されている効率は低く，高効率な Solar-TPV システムを達成するためには，システム全体を俯瞰した研究を行うことが重要である。本論文は高効率 Solar-TPV システムのための設計指針の確立，及び基盤技術の開発と実証に関する研究成果をまとめたもので，全 6 章で構成されている。

第 1 章は序章であり，本研究の背景および目的について述べている。

第 2 章では Solar-TPV システムの全体設計について述べている。本論文では太陽光選択吸収材料への入力エネルギーのエミッタからのふく射熱への変換を定量的に評価できる抽出効率を新たに定義している。この抽出効率と光電変換効率によってシステムの発電効率を記述することで，システムの全体設計の指針の確立を可能としている。また，抽出効率と光電変換効率向上のための太陽光選択吸収材料・波長選択エミッタの光学設計と幾何学設計における設計指針を明らかにしている。

第 3 章では光電変換効率向上に寄与する狭帯域熱ふく射スペクトルを実現する閉口マイクロキャビティ構造を提案している。従来の開口マイクロキャビティ構造に比べて 5 倍以上の高い Q 値をもち，より指向性の小さい放射特性を有する閉口マイクロキャビティ構造の設計に成功している。また，作製した閉口マイクロキャビティ構造から，キャビティ効果による狭帯域化熱ふく射スペクトルが得られることが示唆されている。

第 4 章ではコヒーレントパーフェクトアブソープションに基づいた太陽光選択吸収材料と波長選択エミッタの設計及び作製について述べている。高融点材料であるモリブデンと酸化ハフニウムを用いて，高い耐熱性が期待できる太陽光選択吸収材料・波長選択エミッタの設計に成功している。波長選択性としては光電変換効率 28%以上及び抽出効率 51%以上が期待できる波長選択エミッタと太陽光選択吸収材料の設計に成功している。また作製において，基板の表面粗さを解消することによって近赤外域の放射を抑制の実現できることを見出し，高い波長選択性を持つ太陽光選択吸収材料・波長選択エミッタの作製に成功している。

第 5 章では前章にて構築した設計指針と基盤技術に基づいて，高抽出効率が期待できる平板型太陽光選択吸収材料・波長選択エミッタを用いた発電試験を行っている。平板型太陽光選択吸収材料・波長選択エミッタにおいて抽出効率 44%と発電効率 5.1%を達成している。また，より高い抽出効率が期待できるキューブ型太陽光選択吸収材料・波長選択エミッタにおいて，抽出効率 62%を実験的に得ており，これより発電効率 7.8%が期待できることを明らかにしている。本結果は抽出効率向上が Solar-TPV システムの高効率化に寄与することを実証しているものであり，重要な成果である。

第 6 章は結論であり，各章の成果をまとめている。

以上要するに本論文は，熱ふく射スペクトル制御に基づく Solar-TPV システムの高効率化について研究を行い，高効率 Solar-TPV システムのための設計指針の確立，及び基盤技術の開発と実証に関して有用な成果を得たものであり，機械システムデザイン工学の発展に寄与するところが少なくない。

よって，本論文は博士(工学)の学位論文として合格と認める。